An alternate method to determine the Turbine Shaft system failure due to Sub-synchronous Resonance

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***Abstract**:*Power system is the combination of three crucial process. They are generation, transmission and distribution. Turbine and generator are the most important and sensitive electrical equipment in generation of power. There are various cases where the shaft gets damaged due to the loss in synchronous speed. One such case is generation of resonance due to connected electrical networks. The resonance generated due to the capacitors connected in the line changes the speed of the masses connected in the turbine shaft system. It is necessary to detect the resonance and damp it accordingly. In this paper, sub synchronous resonance and its detection is studied. The study leads to an alternate approach to detect the sub synchronous resonance (SSR) when compared to the traditional techniques.

Index Terms -ANSYS, fatigue, finite element method, MATLAB, shaft, series compensation

I. INTRODUCTION

In India electric power generation mainly depends on thermal power plants. Power system is moving towards renewable energy resources like solar, wind and others. Turbine generator is present in most of the power resources like wind mill, thermal power plant, nuclear power plant, hydroelectric power plant. Since the component is electro mechanical device, the threats are from both mechanical and electrical side. IEEE provides benchmark models to study the turbine generator shaft systems. Sub synchronous oscillation is a situation where the generator runs less than the synchronous speed due to the series compensated transmission line. It will lead to torsional interaction and damages the turbine shaft system. In several cases, the series compensation will increase the stress in the turbine shaft system. Mechanical frequency falls below the electrical frequency in case of SSR [1]. Energy exchange takes place from the grid to the turbine shaft system. The exchange happens during the natural frequencies which is less than the synchronous frequency.

IEEE had provided two benchmark models which explains the mechanical system which includes turbine system and electrical system with synchronous generator. There are two benchmark model available.IEEE Sub Synchronous resonance task force of the dynamic system performance working group in 1977 provided the benchmark model to study the sub synchronous resonance [4].Navajo project has a simple RLC circuit. The resistances in the circuit is constant and the frequency is directly proportional to the reactance in the circuit.A spark gap is provided in the circuit as a protection scheme for the capacitors to make and break the capacitors during faults and reinsertion. Several assumptions are made in the rotor model [2, 3]. Field voltage and torque variation in the exciter is assumed zero. The impedance of the circuit is based on the machine MVA rating and it is different in other power plants. The impedance value changes during the transient condition in the power system.

Mechanical system is exemplified with the inertia and it is related to the kVA of the machine. It is assumed that the steady state exciter torque is assumed to be zero.IEEE benchmark model 2 in fig 1 consists of mechanical system with 4 masses and the electrical system consists of infinite bus connected to the generator through a transformer [7]. The generator here becomes time invariant as the excitation changes the corresponding output also changes. There are two parallel lines in the transmission systems in which one is connected to the power factor correction unit and the other one is connected to the bus. It is clear that the change in power factor changes the frequency which is less than the power frequency [2].

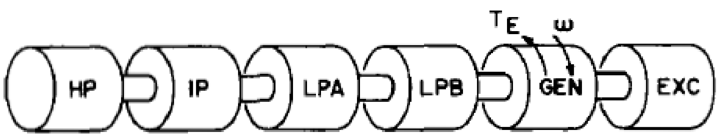

Fig 1 – IEEE Benchmark Model – Mass Inertia representation

The Mechanical system includes different sections such as high pressure (HP), intermediate pressure (IP), low pressure (LP), generator (Gen), and the excitation system (Ex). Crucial parameters which are taken in to consideration for the study of mechanical systems are individual masses of the turbine area, torsional stiffness of the mass and damping coefficient associated with each mass.The concept of sub synchronous oscillation in power system and the impact on the turbine shaft system is studied in this paper.

II. Line Compensation

High voltage and extra high voltage transmission lines are regulated lines. They are regulated for reducing the voltage drop and hence it improves the receiving end voltage. The line compensation level is the ratio of impedance of series capacitors to the impedance of the transmission lines connected to the power plant. Level of compensation is fixed based on the transmission line voltage, terrain of the transmission line and the amount of reactive power required [11]. The probability of SSR formation is where the transmission line compensation exceeds 50% and it is practically not accepted by the power system operation and control unit [2, 7, 8]. The generalized expression for resonant frequency originating in the wind farms is given by

$$f_{rf} = f_0 \sqrt{\frac{X_C}{X_{trf} + X_{txn} + X_{sys}}} \qquad (1)$$

Where

f_{rf} : Resonant frequency in hertz,f_{sys} : System frequency in hertz, X_C : Capacitive reactance in ohms

X_{trf} : Transformer reactance in ohmsX_{txn} : Transmission line reactance in ohmsX_{sys} : System reactance in ohms

The magnetic field produced by the dc excitation and armature interacts each other which results in an electromagnetic torque. The torque is the combination of super synchronous frequency as well as sub synchronous frequency [4]. Energy exchange between turbine and generator happens in the sub synchronous frequency [3].The natural frequency for the series compensated transmission line depends on the line inductance and line capacitance. The relation can also be given in terms of inductive reactance and capacitive reactance.

$$\omega_n = \frac{1}{\sqrt{LC}} = \omega_b \sqrt{\frac{X_C}{X_L}} \qquad (2)$$

Where, ω_n is the frequency of the line and $\omega_b$is the base frequency andX_c, $X_L$are the capacitive reactance and inductive reactance of the line. The capacitive reactance is always lesser than the inductive reactance as the current lags the voltage [5]. It is because of this base frequency will be more than the natural frequency. When the base frequency changes, both sub and super synchronous frequency occurs. This sub synchronous frequency interacts with any of the torsional mode of the turbine shaft and causes fatigue to the system [10].

III. Analytical Techniques

A. Analysis using Eigen value: Linearized differential equations are used in the Eigen value technique. It is used to determine the impact created by the compensation levels in the transmission lines. It can also be related to the torsional modes of the turbine shaft system. Most of the literatures design suitable controllers to counteract the sub synchronous resonance [4]. There are some drawbacks using the Eigen value technique as the controller can be only for small disturbances and it can create positive sequence which is in phase with the rotor system. There are other external criteria where the Eigen value technique create non-linearity especially in the magnetic saturation of the generators as the saturation is not counted in the system model. The situation becomes worst when switching devices especially those are used in TCSC, SVC and STATCOM are involved [5]. These devices are approximated by the system and not the exact values are considered. The devices are connected and disconnected to the transmission lines and makes a great impact in the line reactance. The linear transfer functions are used to represent the switching devices in the transmission line.

*B. Digital time simulation technique:*DTST – Digital Time simulation technique is a programming method and it is used to evaluate the machine-network interactions in the power system. It differs from Eigen value technique where it considers both the linear and nonlinear equations. It allows the user to model the machine based on the power system and controllers. It includes all the equipment in the line including circuit breaker, series or shunt compensation which makes to account the line reactance. It can be also used for studying the torque amplification. The main problem faced in DTST is the time involved in the simulation which is the main reason for not being used in the study of self-excited generators. Electrical systems involve positive sequence and zero sequence data used in the power flow, short circuit data, and resistance values due to the effects of load behavior are used in the programming. Mechanical data which are turbine-generator relative motion from 5Hz to 55Hz are involved in the digital time simulation technique.

C. Frequency Scan Technique:It is the most preliminary technique to identify and mitigate the sub synchronous resonance. It considers the stator voltage at two frequencies which is other than the fundamental frequencies. The rotor current can be determined and it also given as a feedback to the system. In case of difference in the electrical frequency and mechanical frequency, the rotor voltage changes and the voltage is given by the equation (3)

$$V_e = \frac{f_e}{2f_m} \phi_0 \Delta\omega \qquad (3)$$

$V_e$is the voltage generated by the rotor which is in oscillation$f_e$is the electrical frequency,$f_m$is the mechanical frequency of the turbine shaft generator system.$\phi_0$is the flux generated and $\Delta\omega$ is the velocity.

System reactance is plotted against the resistance as a function of frequency. The frequencies where the reactance is not showing any magnitude is the electrical resonant frequencies. If the frequency is negative, it indicates the oscillation is due to induction generator.

IV Alternative approach using Finite Element Method

Finite element method gives the approximate real time solution to the problem which is defined in its workbench.It is useful to determine the stress on the material. It can be used to determine the weak points in the design. In the electric power generation all mechanical structures operate in one or more natural frequencies [16]. The major cause of resonance occurs when the excitation is constant at its natural frequency. Turbine shaft system consists of several stages in the power plant and it is based on the pressure it experiences. Normally the turbine shaft system consists of low pressure system, intermediate pressure system and high pressure system. Normally the shaft system is divided into infinite number of parameters which do not have dependency and so it is difficult to model the turbine shaft system and it depends upon the generator rating and its output and excitation system. The movement of the turbine is taken in counter clockwise direction in several literatures and it represents the positive torque [10]. Inertia and the torque is indirectly proportional to the torque. The electromagnetic torque is considered as the load for the turbine along with the excitation mass coupled along with the shaft system. Torsional vibration can be explained based on the fig 2.IEEE FBS is exemplified by five torsional modes. The last mode is uncontrollable because of the high value of modal inertia. So most of the literature survey restricted from mode-1 to mode-4.

They are also classified into swing mode, super synchronous mode, electromechanicalmode and torsional mode. All the modes is based on the phase reversals and mode 1 has the first low frequency and the nth mode have the nth low frequency [13]. The total number of mode is equal to the number of the total elements providing inertia.Damping of torsional interaction in turbine shaft system depends on the decay of oscillations at a normal torsional mode frequency. Every oscillation has a peak which can be measured and logarithm of ratio of several peak of the oscillation is termed as logarithmic decrement [12]. The logarithmic decrement is same as the decay per cycle when the oscillation is slow. Damping measured is the combination of both mechanical and electrical damping. Mechanical damping is associated with the dissipative force, friction in the bearing, steam force on the turbine blades [13]. Electrical damping is associated with power losses per unit of generator and transmission lines and all these loss components are so sensitive to frequency and amplitude. Modal analysis in the ANSYS will solve the multimass system and give the natural frequencies. The torque and rotating speed of the generator play an important role in determining the Eigen value and it can be solved in ansys workbench after modelling the system in detail.

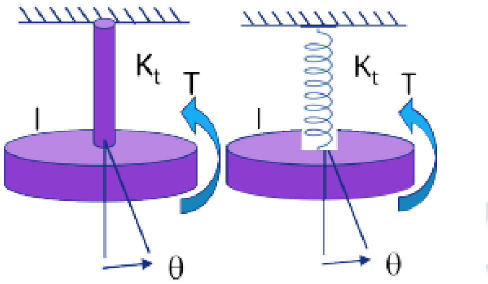

Fig.2 torsional vibration model

The shaft in the fig 2 represents the spring and the disc can be considered as rotational inertia without any deviation. The energy exchange happens between the discs with the top spring which results in a system that twists the natural frequency. K_t is the rotational stiffness, I is the rotational inertia.$\omega_n$is the natural frequency and it is given by the equation 4

$$\omega_n = \sqrt{\frac{K_t}{I}} \qquad (4)$$

V. CASE STUDY - RESULTS AND DISCUSSION USING MATLAB

Using MATLAB Simulink, IEEE Benchmark model 1 is studied in this paper. It consists of 600 MVA/22kV/60 Hz/3600 rpm synchronous machine connected to the infinite bus through transmission lines. The line is compensated by series capacitors and the maximum compensation value is around 55% [11]. The sub synchronous mode is introduced by the series capacitor compensation unit which is connected to the line after a three-phase fault. Torque amplification phenomenon is observed in the multimass shaft model. In Fig 3. A peak torque of 2 pu is occurred for 45% series compensation and 4 pu for 55% series compensation and this is the reason that the series compensation is limited for the power flow in the high voltage transmission line.Fig 4 shows the peak torque of 4 pu. In Fig 5 the torque deviations based on the speed for the three masses in the benchmark model. The deviation becomes more when the series compensation increases.In Table I the input parameters of the IEEE first bench mark model are adopted as standard [11, 12]. and in Table II various output parameter is shown for the change in compensation level. MATLAB Simulink do not give the exact point of weakness in the turbine generator shaft system. Modal analysis gives the stress point as Finite element method is used. [16]

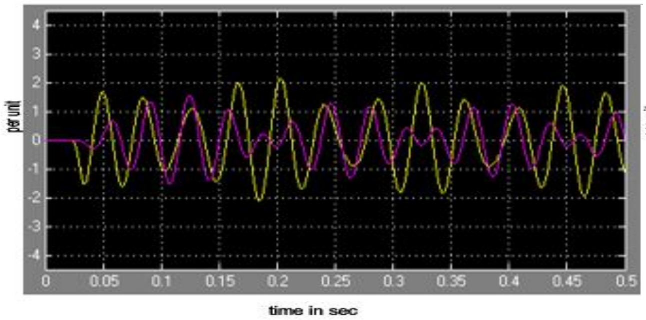

Fig 3. Series compensation – 45%

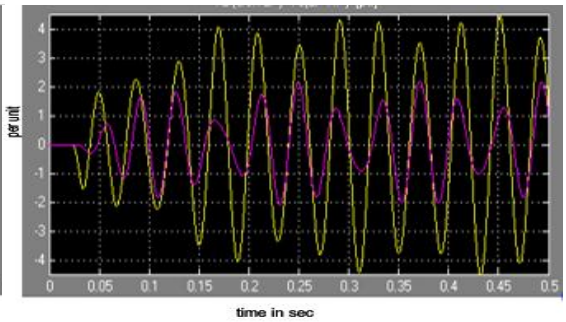

Fig 4. Series compensation – 55%

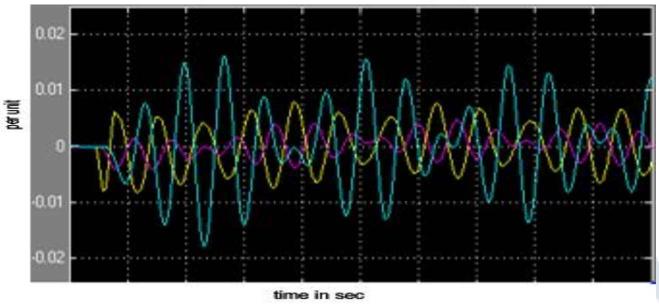

Fig 5. Torque deviation of three mass in turbine shaft system– 55%

TABLE I Input parameters

SL NO	Parameter	Input value
1	Nominal Rating	600 MVA
2	Phase voltage	22kV
3	Phase current	38.745 Amps
4	Real Power	5.8208e-011
5	Reactive power	1.476 MVAr
6	Mechanical power developed	16.348 W
7	Torque	0.86729 N.m

TABLE II output parameters

SL NO	Compensation level	Peak torque (pu)	Turbine shaft system oscillation (pu)		
			Mass 1 (Gen)	Mass 2 (LPT)	Mass 3 (HPT)
1	25	1.5	0.004	0.006	0.008
2	35	2	0.004	0.007	0.013
3	45	3	0.004	0.008	0.017
4	55	4	0.004	0.012	0.027

VI. CONCLUSION

In this paper, the basics of sub synchronous resonance and its impact on the power system is studied. Various literatures review sub synchronous resonance with IEEE Benchmark models having 5 mass system and 3 mass system. MATLAB SIMULINK model of steam turbine and governor system shows the peak torque which increases with the compensation level. It is also to be noted that in the benchmark model the first mass represent the generator, second mass represents the low pressure turbine and the third mass represents the high pressure turbine. As the level of compensation increases, the third mass of the system is oscillating more when compared to the other two mass of the system. There is a possibility to use Finite element method to solve the stability analysis and to determine the stress in the turbine shaft system. MODAL analysis can be used instead of solving the problem using traditional technique like Eigen value estimation, Frequency scanning and digital time simulation techniques.

VII. REFERENCES

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